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A MODULE EXPERIMENTAL PROCESS SYSTEM DEVELOPMENT UNIT (MEPSDU)

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May 1, 1981 - August 31, 1981

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SOLAREX CORPORATION

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The JPL Flate-Plate Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initial a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE.

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ABSTRACT

The purpose of this program is to demonstrate the technical readiness of a cost-effective process sequence that has the potential for the production of flat plate photovoltaic modules which met the price goal in 1986 of 70¢ or less per Watt peak.

During the quarter, program efforts included:

- Cell fabrication using the proposed process sequence;
- Optimization of cell processes;
- Identification and testing of insulator tapes and edge seal material;
- Optimization of a lamination procedure;
- Evaluation of encapsulation materials;
- Identification, discussions, demonstrations and visits with candidate equipment vendors;
- Selection of and initiation of a tabbing and stringing machine subcontract;
- Updating the drawing package and QA plan;
- Collecting data for preliminary Samics cost analysis.

QUARTERLY REPORT

TABLE OF CONTENTS

1.0 Introduction

The purpose of the MEPSDU program is to demonstrate the technical readiness of a cost-effective process sequence that has the potential to produce flat-plate photovoltaic modules which meet the 1986 price goal of less than $.70 per peak Watt. To achieve this goal, Solarex will design, develop and fabricate a Module Experimental Process System Development Unit (MEPSDU) and will utilize the unit to produce a quantity of modules using the proposed process sequence. This effort will include:

- Design of a detailed cost effective process sequence,
- Completion of a detail design of the MEPSDU,
- Fabrication and assembly of the MEPSDU,
- Preparation of a process instruction manual, including in-line process control information,
- Performance of a minimum of three technical demonstrations which will include the production of sufficient modules and production data to permit validation of the contract goal,
- Performance of a cost analysis of the process sequence, including a study of the cost impact and changes required in the MEPSDU to allow the use of different types of input material.

In selecting a process sequence, we have emphasized the following considerations:

- Economics,
- State of verification,
- Availability of equipment for automation,
- Ease of integrating individual processes,
- Compatibility with the selected input material and a variety of other alternative silicon sheet materials.

In our design of the MEPSDU, we have chosen to develop a unit that is a forerunner of a production facility. This means that we will utilize production equipment, not laboratory-scale equipment. All manual handling of individual cells will be eliminated.

The concept of the MEPSDU is to demonstrate the process sequence and machinery by utilizing a single, rather than several parallel machines for each station. This means that the line itself is not a balanced production line, but all of the throughput rates are sufficient to demonstrate automated manufacture. Indeed, this unit itself will be capable of producing close to 10 MW per year with only minor modification (e.g. addition of several more laminating stations).

The baseline process sequence is described in Section 2.1. Proposed changes in this baseline are described in Section 2.2.

Results of experiments performed in the third quarter are presented in Section 3. Section 4 summarizes our progress to date, including recommendations and conclusions, as well as presenting a brief schedule for the next quarter.

2.0 Process Description

2.1 Baseline Process Sequence

The baseline process sequence is shown in block form in Figure 1. This process sequence was described in detail in the First Quarterly Report (1). The baseline process sequence includes the following features:

- Semicrystalline silicon (10 cm x 10 cm) as the silicon input material;
- Spray-on dopant diffusion source;
- Al paste BSF formation;
- Spray-on AR coating;
- Electroless Ni plate-solder metallization;
- Laser scribe edges;
- Solder reflow tabbing and stringing machine; and
- Laminated EVA modules on glass superstrate.

2.2 Proposed Changes in Process Sequence

As described in the Second Quarterly Report (2), the laser scribing technique has proved unsatisfactory when coupled with a negative screen printed metallization process. A number of alternatives have been proposed and are under investigation as described in Section 3.

Figure 1

GENERAL PROCESS DESCRIPTION

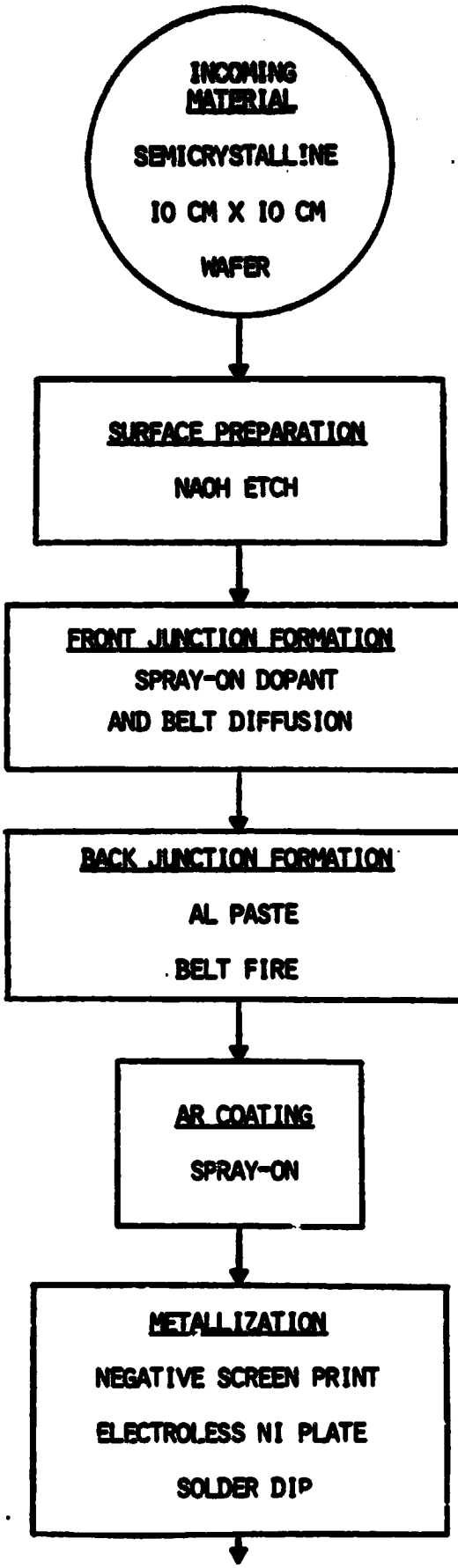
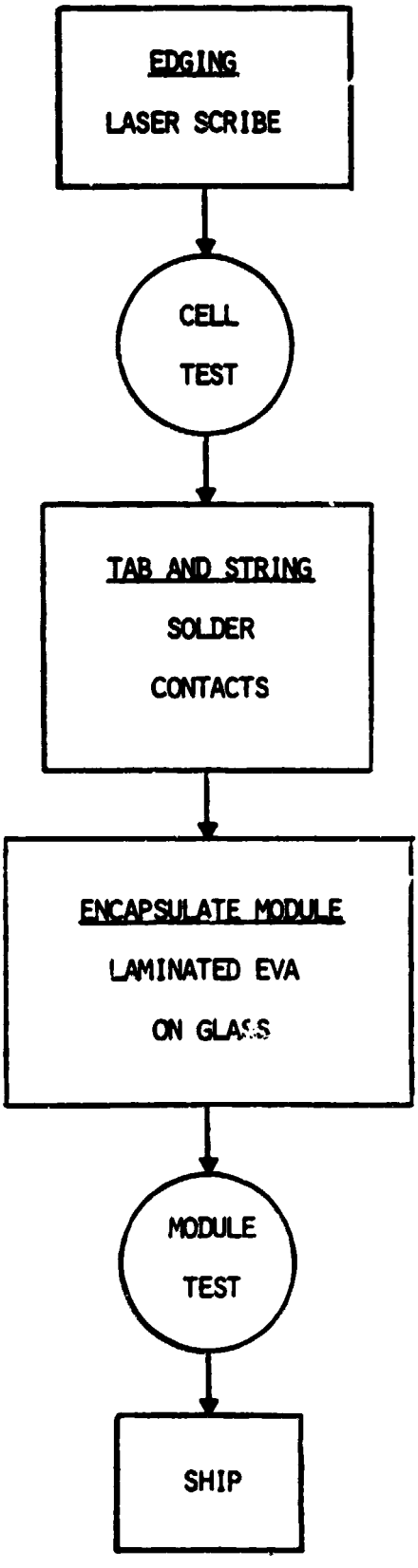


Figure 1 (cont'd)



The original process sequence specified HCl etch clean-up of the Al paste residues. The baseline process now utilizes an abrasive (glass bead) clean-up of the residues, leaving the bulk of the conducting Al in place. This Al can then provide the needed back metallization conductivity without addition of additional metal, i.e., solder. The backs will still be Ni plated to allow them to be interconnected. However, no additional solder will be added to the backs. The fronts will be wave soldered instead of solder dipped. Wave soldering is a highly controllable process that has replaced solder dipping in the printed circuit board industry. It should improve solder uniformity and controllability as well as reducing the amount of solder required for the process.

3.0 Technical Progress

3.1 Documentation

The following technical documents were submitted during this quarter:

12. Quarterly Technical Report No. 2
13. Technical Progress Report No. 7
14. Technical Progress Report No. 8
15. Technical Progress Report No. 9
16. Revised Drawing Package

3.2 Cell Processing Experiments

A summary of all cell fabrication experiments conducted since the beginning of the program appears in Table 1. Experiments 12 through 21 were conducted this quarter. The following sections describe these experiments. (Refer to Table 1 for actual performance measurements).

TABLE #1

SUMMARY TABLE OF CELL FABRICATION EXPERIMENTS

Lot	Description of Experiment	Silicon Type and Size	Diffusion Conditions	Metallization	Yield	Results and Comments
1	Hand-sprayed phorphoro-film dopant	3" round s.c.	Tube, in He (half of wafers) or air @ 850°C			Uneven and heavy oxide - could not remove oxide.
2	Machine-sprayed dopant @ 5 cc/min. (A) and 10 cc/min. (B)	3" round s.c.	Tube, in O_2 @ 910°C for 10 min.			No significant difference in sheet resistivity between groups; oxide was removable in 5% aqueous HF.
3	Compare phosphorofilm with "homemade" Solarex formulation-dopant	3" round s.c.	Tube, in O_2 @ 910°C for 10 min.			Phosphorofilm wetting was greatly superior, resulted in uniform oxide and sheet resistance measurements. Solarex formulation did not wet satisfactorily, resulted in spotty oxide.
4	Evaluate front junction	(3" round s.c.) 2 x 2 cm cells	Tube, in O_2 @ 910°C for 10 min.	TiPdAg	83%	Cells were processed via MEPSDU Process through diffusion, then standard "space" process. Results indicate that diffusion quality is good: $\bar{P}_{max}$ = 69.3 mW (AMO).
5	Evaluate front junction formation with gaseous vs. spray doping	2 x 2 cm cells semi.	Tube, in O_2 @ 910°C for 10 min.	TiPdAg	80%	The average power was the same for both groups, but voltage is lower in sprayed group than in gaseous-doped group.
6	Evaluate machine-sprayed junction	2 x 2 cm cells semi. and s.c.	Tube, in O_2 @ 910°C for 10 min.	TiPdAg	64% semi. 80% s.c.	Processing generally improved over Lot 5. Junction looks uniform.

	P_{max}	I_{sc}	V_{oc}	(AM1)
Gaseous	43.1 mW	108 mA	559 mV	
Sprayed	43.1 mW	105 mA	545 mV	

	P_{max}	I_{sc}	V_{oc}	(AM1)	$\overline{FF}$
Semi.	49.1 mW	114 mA	574 mV		.75
S.C.	63.0 mW	136 mA	596 mV		.78

TABLE #1 (Cont)

Lot	Description of Experiment	Silicon Type and Size	Diffusion Conditions	Metallization	Yield	Results and Comments
7	Evaluate diffusion temperature and uniformity	10 x 10 cm semi. cells	Tube, in O_2 for 10 min. @ 910°C (P_{sh} = 32 Ω/□) 900°C (P_{sh} = 38 Ω/□) 890°C (P_{sh} = 41 Ω/□) 880°C (P_{sh} = 56 Ω/□) 870°C (P_{sh} = 72 Ω/□)			Sheet resistivity measurements showed slight scatter, but generally increased with decreasing diffusion temperature. All oxide was easily removable in aqueous HF (5%).
8	Evaluate belt diffusion	10 x 10 cm semi. cells	Manuf. profile on belt diffusion furnace (900°C max. temp.) ambient air			Experimental cells not finished due to wafer problem. Sheet resistivity measurements varied 26-52 Ω/□.
9	Prepare cells using diffused wafers from Lot 7	2 x 2 cm cells	See Lot 7	TiPdAg	Not calculated	Cell performance improved with decreasing temperature. Additional sintering of cells (at later date) to remove possible series resistance caused slight average improvement to two groups:

Temp. (°C)	P_{sh}	P_{max} (mW)	I_{sc} (mA)	V_{oc} (mV)	FF	ZEff.
870°C	72 Ω/□	40.4 mW	98 mA	556 mV	.738	10.1 %
	*After sinter	40.4 mW	97 mA	564 mV	.738	10.1 %
880°C	56 Ω/□	40.0 mW	97 mA	553 mV	.746	10.0 %
	*After sinter	41.3 mW	98 mA	556 mV	.745	10.3 %
890°C	41 Ω/□	38.2 mW	96 mA	549 mV	.725	9.5 %
	*After sinter	38.2 mW	95 mA	558 mV	.721	9.5 %
900°C	38 Ω/□	37.4 mW	95 mA	551 mV	.714	9.35%
	*After sinter	39.4 mW	96 mA	562 mV	.730	9.8 %
910°C	32 Ω/□	34.0 mW	88 mA	540 mV	.715	8.5 %
	*After sinter	34.0 mW	89 mA	552 mV	.692	8.5 %

*Additional 30 sec. sinter and retest @ AM1, 25°C.

Lot	Description of Experiment	Silicon Type and Size	Diffusion Conditions	Metallization	Yield	Results and Comments
10 A,B,C	Compare belt-diffused cells (two sizes) with tube diffused	A: 2 x 2 cm B: 2 x 2 cm C: 10 x 10 cm cells, all semi.	A&C: Belt-diffused with MEPSDU profile B: Tube, in O_2 for 10 min.	A: TiPdAg B: TiPdAg C: Ni/Solder	See chart.	Cell performance low in all groups. Subsequent additional sintering did improve groups A and B. Group C could not be sintered (Ni/Solder). Results - next page.

TABLE #1 (Cont)

Lot	Description of Experiment	Silicon Type and Size	Diffusion Conditions	Metallization	Yield	Results and Comments
10 Cont'd.						Lot 10A / Lot 10B / Lot 10C
						P_{max} 26.8 mW / 24.4 mW / 430 mW
						*After sinter- 32.0 mW / 31.6 mW
						I_{sc} 74.0 mA / 83.0 mA / 1,462 mA
						*After sinter- 80.0 mA / 86.0 mA
						V_{oc} 532.0 mV / 493.0 mV / 536 mV
						*After sinter- 552.0 mV / 551.0 mV
						Eff. 6.70 % / 6.10 % / 4.3 %
						*After sinter- 8.0 % / 7.9 %
						Yield 87.0 % / 92.0 % / 32.0 %
						*Additional sinter (30 sec.) and retest @ AM1, 25°C.
11 A&B	Compare belt diffusion with tube diffusion	A&B: 2 x 2 cm semi. cells 2 x 2 cm s.c. cells	A: Tube, @ 910°C for 10 min. B: Belt, @ 910°C MEPSDU	TiPdAg TiPdAg	Approx. 80%, all groups	Tube diffused cells better than belt diffused, regardless of silicon type; single crystal cells better than semi by both methods. Additional sintering caused little change in average performance.

A.

	Semicrystalline	Single Crystal
Pmax	34.7 mW	39.2 mW
Voc	547 mV	556 mV
Isc	90 mA	101 mA
FF	0.705	0.7
Eff (AM1-25°C)	8.7 %	9.8 %
No. of Cells	90	42

B.

	Semicrystalline	Single Crystal
Pmax	30.2 mW	35.6 mW
Voc	535 mV	548 mV
Isc	78 mA	87 mA
FF	0.724	0.742
Eff (AM1-25°C)	7.55 %	8.9 %
No. of Cells	90	47

TABLE #1 (Cont)

Lot	Description of Experiment	Silicon Type and Size	Diffusion Conditions	Metallization	Yield	Results and Comments
12 A,B,C	Evaluate diffusion temperature for large cells	A,B,C: 10 x 10 cm semi. cells 3" round s.c. cells	A: 910°C tube, in O_2 for 10 min. B: 890°C tube, in O_2 for 10 min. C: 875°C tube, in O_2 for 10 min.	All groups Ni/Solder	Semi: 60% S.C.: 0	Verified that lower-temperature diffusion appears to give better results. Current and power are highest in Group C (875°C).

	Lot 12A	Lot 12B	Lot 12C
Diffusion Temperature	910°C	890°C	875°C
P_{max}	0.85 W	0.86	0.875
I_{sc}	2.26 A	2.27 A	2.27 A
V_{oc}	544 mV	544 mV	545 mV
Eff	8.5 %	8.6 %	8.75 %
FF	0.7	0.7	0.71

Lot	Description of Experiment	Silicon Type and Size	Diffusion Conditions	Metallization	Yield	Results and Comments
13	Standard MEPSDU process to fabricate panel cells					All wafers broken in spin drier accident after etch.
14	Standard MEPSDU process to fabricate panel grade cells	10 x 10 cm semi. cells	Tube, @ 910°C in O_2 for 10 min.	Ni/Solder	64%	Lot average 7.8% AMI.

	Lot 14
P_{max}	0.815 W
I_{sc}	2.144 A
V_{oc}	552 mV
Eff	8.15 %
FF	0.69
Yield	64 %

TABLE #1 (Cont)

Lot	Description of Experiment	Silicon Type and Size	Diffusion Conditions	Metallization	Yield	Results and Comments
15	Demonstrate MEPSDU process and determine oxide thickness	10 x 10 cm semi. cells 3" round, polished 2 x 2 cm cells	All: Tube, @ 910°C in O_2 for 10 min.	10 x 10 cm, 3" round: Ni/Solder 2 x 2 cm: TiPdAg	60%	Established oxide thickness variation - 480 to 1,100 Å. Lot average (10 x 10 cm): 8.0% Eff. (3" round): 7.5% Eff. (2 x 2 cm): 12.1% Eff.

	Semi-crystalline 10 x 10s	Single Crystal 3"	Single Crystal 2 x 2s
P_{max}	0.816 W	0.34 W	0.0485
I_{sc}	2.2 Amp.	1.13 Amp.	0.114
V_{oc}	543 mV	530 mV	573 mV
Eff	8.16 %	7.6 %	12.1 %
FF	0.68	0.57	0.74
Yield	60		

TABLE #1 (Cont)

Lot	Description of Experiment	Silicon Type and Size	Diffusion Conditions	Metallization	Yield	Results and Comments
16	Prepare samples for wave solder and plasma etching experiment	10 x 10 cm semi. 3" round s.c.	Tube, @ 910°C for 10 min.			One half of samples shipped to Electrovert for wave soldering. One half of samples shipped to Technics for plasma etching.
17	Evaluate screenable oxide paste as diffusion mask (apply annulus)	3" round	Tube, @ 910°C			Used Engelhard overglaze #A3031. When fired, paste "ran" into cell center. Need higher temperature oxide paste.
18	Verify lower diffusion temperature	10 x 10 cm semi. 3" round s.c. controls	Tube, in O_2 @ 890°C	Ni/Solder	76% semi. 75% single	Current density improved as a result of lower diffusion temperature, but average cell performance adversely affected by non-continuous front contacts (metallization incomplete) on one cassette's cells:

n	Isc (mA)	Voc (mV)	Pmax (mW)	Eff. (%)	Current Density, mA/cm² Blue	Red	Fill Factor
38 (All)	2314	539	746	7.46	6.00	13.78	.598
23 (OK contacts)	2384	545	835	8.35	6.00	13.81	.643
6 single crystal	1225	578	488	10.7	5.94	16.32	.689

19	Use 100 mesh s.s. screen to apply aluminum ink	10 x 10 cm semi. 3" round s.c. controls	Tube, in O_2 @ 910°C	Ni/Solder	38% semi. 60% single	Current density and open circuit voltage improved over 150 mesh screen with similar processing:

TABLE #1 (Cont)

Lot	Description of Experiment	Silicon Type and Size	Diffusion Conditions	Metallization	Yield	Results and Comments
20	Belt vs. tube diffusion	10 x 10 cm. semi. 3" round	A. Tube, in O_2 @ 910°C B. Convection belt @ 910°C. in ambient	Ni/Solder	A. 44% B. 44%	This run showed that belt-diffused cells performed better than tube-diffused.

	n	Isc (mA)	Voc (mV)	Pmax (mW)	Eff. (%)	F.F.	Current Density (AM1)
Semi	13	2372	554	797	7.97	0.61	23.7
Single	2	1075	551	349	7.65	0.59	23.6

		n	Isc (mA)	Voc (mV)	Pmax (mW)	Eff (%)	F.F.	AM1	Blue	Red
A.	Semi	11	2210	551	744	7.4	.61	22.1	5.33	13.34
	Control	1	1137	551	255	5.6	.41	24.9	5.26	16.27
B.	Semi	11	2358	554	784	7.8	.60	23.4	5.49	14.40
	Control	5	1029	567	287	6.3	.48	22.6	4.98	15.09

Lot	Description of Experiment	Silicon Type and Size	Diffusion Conditions	Metallization	Yield	Results and Comments
21	Compare alloy techniques: A) Tube B) Resistance heat belt C) IR belt	Each group 10 x 10 cm. semi. 3" round s.c.	Tube, in O_2 @ 890°C	Ni/Solder	A. 35% B. 37.5% C. 47%	Open circuit voltage and fill factor are as high in Group C as in Group A; current density was highest in Group C. Single crystal controls for Group A appear anomalously low. Metallization integrity remains a problem.

TABLE #1 (Cont)

Lot	Description of Experiment	Silicon Type and Size	Diffusion Conditions	Metallization	Yield	Results and Comments							
						n	Isc (mA)	Voc (mV)	Pmax (mW)	Eff. (%)	F.F.	AM1	Blue	Red
					A. Semi	11	2412	554	827	8.3	.62	24.12	6.09	14.32
					Controls	3	1086	545	295	6.5	.50	23.81	5.37	15.96
					B. Semi	8	2273	548	652	6.5	.52	22.73	5.97	13.68
					Controls	2	1273	558	390	8.6	.55	27.9	6.18	17.5
					C. Semi	11	2427	554	887	8.9	.66	24.27	5.98	14.57
					Controls	2	1244	554	388	8.5	.56	27.3	6.22	17.4

Lot 12

This experiment compared the effect of varying sheet resistivity. Three groups of wafers were prepared for diffusion via MEPSDU surface preparation and spray doping. The diffusions were done in a quartz diffusion tube in oxygen atmosphere for ten minutes. The lowest-temperature diffusion (875°C) produced the best cells, 8.75% average (9.2% best cell - unencapsulated). The yield of semicrystalline wafers was 60 percent.

Lot 13

This experiment was designed to produce cells for use in panel experiments. All the wafers were broken due to equipment failure.

Lot 14

This group of cells was prepared to be used in module experiments. Processing included MEPSDU surface preparation, doping, diffusion (tube, 910°C, oxygen, $\rho sh = 20\text{-}25\Omega/\square$) aluminum paste alloy (850, tube, atm), HCl back cleanup, spray AR, and nickel-solder metallization. The output power was slightly lower than the results from lot 12 probably due to a variation in AR coating uniformity.

Lot 15

This group of cells was prepared to demonstrate the MEPSDU process (especially spray-doping) to JPL personnel and generate more panel-grade cells. The process was essentially the same as Lot 14. The single crystal cells were lower than expected due to shunting as a result of Al paste on the front, since there was a problem aligning the screen. The 2 cm x 2 xm cells were processed from polished <110> wafers using MEPSDU diffusion, but TiPdAg metallization with no AR. The diffusion oxide was measured on the ellipsometer and found to range between 420 Å and 1,100 Å (edge to center). The current densities were very high for such cells without AR coating. The semicrystalline results were similar to Lot 14.

Lot 16

This experiment was used to prepare samples for wave soldering and plasma etching experiments. Samples of 10 cm x 10 cm semicrystalline and 3" round single crystal silicon were processed by the standard MEPSDU procedure through electroless Ni deposition and resist cleanup. The samples were then split with half being shipped to Electrovert for wave soldering of the fronts while the other half was sent to Technics for ion milling of the edges. The ion milling experiments are described in Section 3.5.

Lot 17

This was the initial experiment to evaluate a variety of screenable oxides for use as an edge protection during diffusion and Ni plating. This experiment utilized Englehard Overglaze #3031. The working temperature (≈500°C) of this material is lower than MEPSDU process temperatures and the problem encountered was the migration of the paste across the cell surface - probably the direct result of the high firing temperature (910°C).

Lot 18

This experiment utilized a 890°C diffusion temperature with all other processes similar to Lots 12, 14, and 15. The current densities in Lot 18 were higher confirming that lower diffusion temperatures yield better current collection. One cassette of cells exhibited series resistance problems attributable to non-continuous solder coatings on the grid lines.

Lot 19

This experiment was designed to investigate the effect of utilizing a 100 mesh screen for aluminum paste application, rather than the 150 mesh screen used in earlier experiments. A diffusion temperature of 910°C was used with all but mesh size similar to Lots 12, 14, and 15. Lot 19 exhibited higher open circuit voltage and better short circuit current than these earlier lots.

Lot 20

This experiment was designed to compare belt diffusion with tube diffusion. The diffusion temperature was 910°C. Belt-diffusion yielded improved current and higher output power than the tube diffusion. Both lots were lower than the 890°C cells from Lot 18.

Lot 21

This experiment was designed to compare tube alloy with infrared belt alloy and with convection belt alloy. The infrared belt yielded the best cell performance, with tube second and convection belt poorest. It should be noted that the profile for the infrared belt and tube have been optimized for semicrystalline silicon while the convection belt is optimized for single crystal silicon.

During a number of experiments the performance of the single crystal controls has been worse than that of the semicrystalline silicon. This effect has become more pronounced as we have optimized the processes for the semicrystalline material. These results indicate that the semicrystalline and single crystal silicon required different process parameters to achieve optimum cell performance.

3.3 Pilot Line Cell Processing

Because of the need to provide cells for fabrication of preprototype modules, a series of pilot cell process runs were begun. Three such lots have been completed to date. The results are given in Table 2. The following sections describe each run.

Pilot Run #1

Utilizing the results of Lots 18 and 19, the cells were diffused at 890°C and alloyed using a 100 mesh screen. Because of the coarser screen, aluminum "balls" formed on the back of the wafers during the alloy step. While the "balls" dissolved during the HCl back etch, they left highly textured craters that resulted in a high breakage rate, especially during solder dipping.

Pilot Run #2

Because of the problem associated with the aluminum "balls" in Pilot Run #1, a 150 mesh screen was used in Pilot Run #2. All other processing was identical. This run suffered low yield due to series resistance problems. There was a definite metallization problem associated with thin and non-continuous front solder. The problem appears to be related to inadequate clean-up of the resist after nickel plating. A larger, more powerful ultrasonic bath will be utilized for future resist removal.

Table 2. Pilot Line Summary

	# STARTS	YIELD (90%)	EFF.	CURRENT DENSITY AMI	RED	BLUE	VOC	CELLS 8%	NOTES
Semi	250	27 %	7.2 %	23.30	13.52	6.10	541	41	
Single	25	64 %	7.6 %	22.97	14.29	5.31	528		
Semi	246	37.8%	7.5 %	23.56	13.73	6.12	542	72	
Single	25	80 %	8.9 %	25.7	16.35	5.73	554		
Semi	250	15.6%	7.6 %	25.30	16.00	6.68	530	30	Lost 175 cells due to heavy oxide.
Single	25	24 %	9.45%	26.7			562		

Pilot Run #3

Due to operator error during the manual spraying of the diffusion dopant, too thick a layer was deposited. The oxide could not be removed on 70% of the wafers. The remainder of the lot did not suffer from the problems of Lots 1 and 2, and resulted in a reasonable number of cells above 8% efficiency.

3.4 AR Coating Experiments

The initial experiments were designed to find an organic alcohol compatible with the AR coating material that could be utilized in a pre-spray step. The first attempt utilized the components of the AR spray itself. The results are summarized below:

1. N-Butyl Acetate: Dried as the wafer was sprayed.
2. Sec-Butanol: Dried as the wafer was sprayed.
3. Isopropyl Alcohol: Dried as the wafer was sprayed.
4. 2 Ethyl - 1 Hexanol: Boiling point too high. It evaporated with the AR on top of it, resulting in the formation of pools with a very uneven AR.

A number of solvents with a boiling point near 150°C were ordered. These included: 3 methyl-1-butanol, 2 ethoxy-ethanol, Hexyl Alcohol, Hexanol, and Pentanol. Experiments of prespraying with 3-methyl-1-butanol, 1-Hezanol, Pentanol and Hexyl Alcohol resulted in no change in the subsequent AR coating. Prespraying with 2 ethoxyethanol resulted in a spotty surface. A number of experiments with 3-methyl-1-Hexanol both as a pre-spray and as a replacement for the Sec-Butanol, resulted in inconsistent AR coatings.

At this point we stopped looking for a prespray treatment and began to investigate the effect of deposition conditions on the AR coating. It was found that if Titanium Isopropoxide is sprayed directing on a heat wafer (450 to 500°C) a uniform blue color can be obtained. Placing the wafer on a hot plate at 450-500°C and spraying the Titanium Isopropoxide with an air brush resulted in reproducible uniform AR coatings. Figure 2 is a plot of Reflection plus Transmission as a function of wavelength for one sample of semicrystalline Si sprayed in this manner. This compares favorably with evaporated AR coatings.

An experiment was conducted in which 2 cm x 2 cm single crystal cells with TiPdAg contacts were tested before AR coating. Half the cells were then given a Ta_2O_5 evaporated AR coating while the other half were AR coated using the new hot spray technique. The results are summarized in Table 3. It is apparent that the hard spraying technique does not produce as even a coating as the evaporated AR. However, the use of automated spraying equipment should alleviate this problem and result in

FIGURE 2

HOT SPRAY AR COAT Ti ISOPROPOXIDE

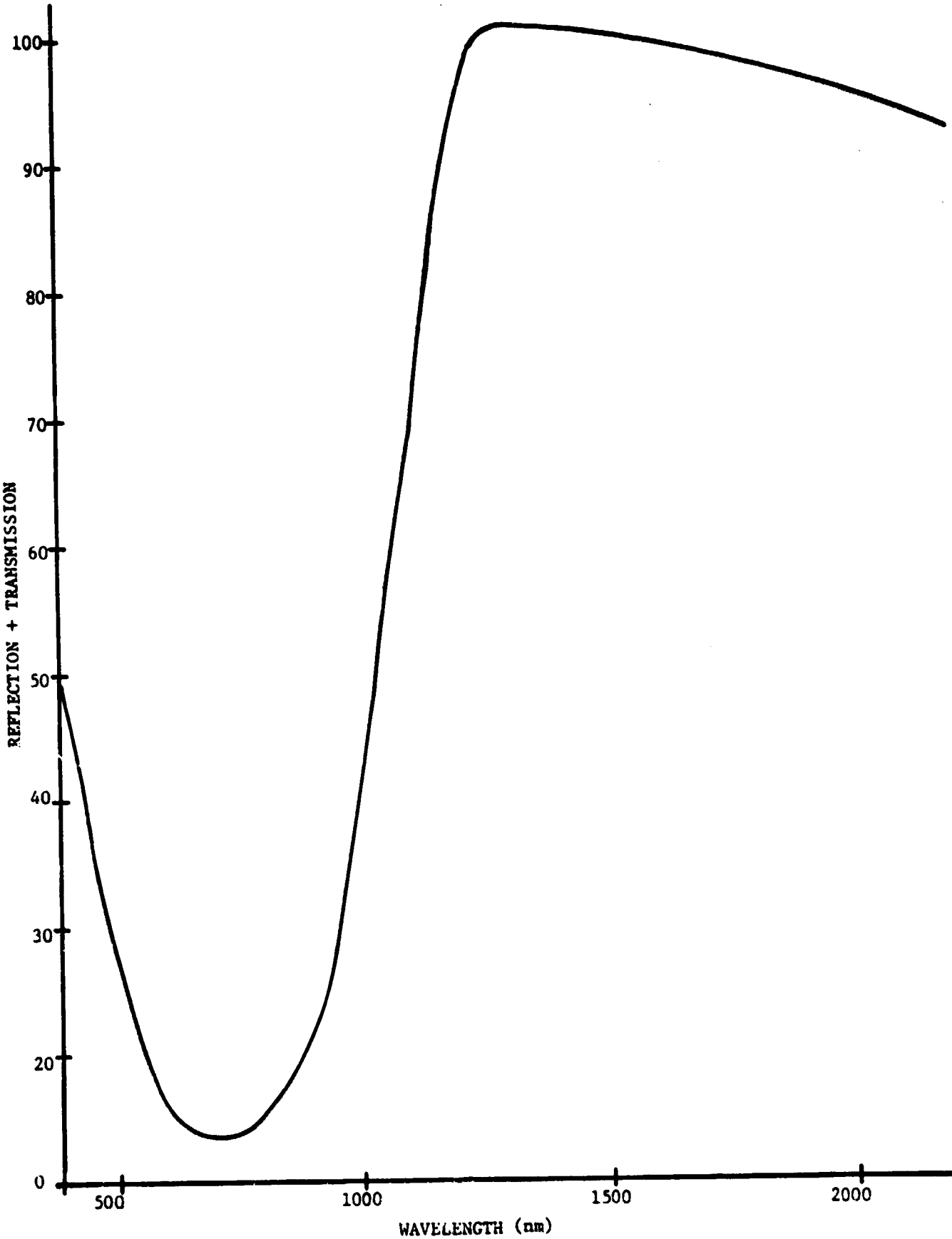


Table 3. AR Coating Experiment

	Evaporated Ta_2O_5 Cells	Sprayed TiOx Cells
Increase in Open Circuit Voltage	6 mV	12.5 mV
Increase in Short Circuit Current	40.2 mA	36.5 mA
Increase in Peak Power	18.5 mW	19.5 mW

AR coatings as effective as those produced by evaporation.

3.5 Ion Milling

Samples from Lot 16 were delivered to Technics Ion Microfabrication Systems, Inc. after nickel plating. The edges were then ion milled in a Model #MIM TLA20 Ion Milling Machine. The beam voltages, currents, and etch times are given in Table 4.

The samples were then returned to Solarex where they were solder dipped and tested. Some cells in Batch #3 and #4 were only moderately shunted while the remainder were severely shunted. Several cells in Batch #5 had acceptable shunt resistance values while the remainder were moderately shunted. It appears that the treatment in Batch #5 was marginally successful.

A second set of samples was taken to Technics Ion Microfabrication Systems, Inc. for ion milling experiments. The ion milling was performed at 1400 volts with a beam current of 0.26 mA/cm^2 for 90 minutes. There was no metallization visible on the edge but all 25 cells were shunted. These were not edge shunted, however. The shunting may have been due to overheating of the wafers or problems with cell processing. Further experiments are required to verify that ion milling is a viable edging technique.

As part of the efforts to better understand edging, a cost analysis of the ion milling step was performed. Format A describing the process is attached as Table 5. It is based on using a Technics machine in which 1000 wafers are stacked for a 1 hour

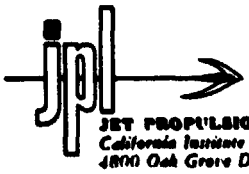
Batch #	Beam Voltage	Beam Current	Time
1	740 V	0.5 mA/cm^2	24 min.
2	750 V	0.5 mA/cm^2	48 min.
3	750 V	0.5 mA/cm^2	60 min.
4	1100 V	0.7 mA/cm^2	48 min.
5.	1100 v	0.7 mA/cm^2	60 min.

Table 4. Ion Milling Parameters

TABLE 5

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT A



JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr. / Pasadena, Calif. 91103

PROCESS DESCRIPTION

Note: Names given in brackets [ ] are the names of process attributes requested by the SAMIS III computer program.

A1 Process [Referent] EDGEM

A2 [Descriptive Name] Ion Mill Edge of Cells

PART 1 – PRODUCT DESCRIPTION

A3 [Product Referent] CellM

A4 Descriptive Name [Product Name] Edged Wafers

A5 Unit Of Measure [Product Units] Wafers

PART 2 – PROCESS CHARACTERISTICS

A6 [Output Rate] (Not Thruput) 16.6 Units (given on line A5) Per Operating Minute

A7 Average Time at Station [Processing Time] 90 Calendar Minutes (Used only to compute in-process inventory)

A8 Machine "Up" Time Fraction [Usage Fraction] .95 Operating Minutes Per Minute

PART 3 – EQUIPMENT COST FACTORS [Machine Description]

A9	Component [Referent]	MILL	STACK	COLD TRAP
A9a	Component [Descriptive Name] (Optional)	Ion milling machine	Stack loader	Refrigera
A10	Base Year For Equipment Prices [Price Year]	81	81	81
A11	Purchase Price ($ Per Component) [Purchase Cost]	105,000	14,500	5,000
A12	Anticipated Useful Life (Years) [Useful Life]	10	5	5
A13	[Salvage Value] ($ Per Component)	20,000	1,000	
A14	[Removal and Installation Cost] ($/Component)	2,000		

Note: The SAMIS III computer program also prompts for the [payment float interval], the [inflation rate table], the [equipment tax depreciation method], and the [equipment book depreciation method]. In the LSA SAMICS context, use 0.0, (1975, 6.0), DDB, and SL.

Format A: Process Description (Continued)

A15 Process Referent (From Page 1 Line A1) EDGEM

PART 4 – DIRECT REQUIREMENTS PER MACHINE (Facilities) OR PER MACHINE PER SHIFT (Personnel)
[Facilities and Personnel Requirements]

A16 Catalog Number [Expense Item Referent]	A18 Amount Required Per Machine (Per Shift) [Amount per Machine]	A19 Units	A17 Requirement Description
A2064D	120	Sq. ft.	Floor space
B3752D	0.20	PRSN x YRS	Machine operator
B3688D	0.05	PRSN x YRS	Maintenance

PART 5 – DIRECT REQUIREMENTS PER MACHINE PER MINUTE
[Byproduct Outputs] and [Utilities and Commodities Requirements]

A20 Catalog Number [Expense Item Referent]	A22 Amount Required Per Machine Per Minute [Amount per Cycle]	A23 Units	A21 Requirement Description
C1032B	0.125	Kwh	Electricity
C1128D	0.134	ft^3	Cooling water
E1112D	0.001	ft^3	Argon
DSLRX06	0.01	$	Filaments
DSLRX07	.006	$	Spare parts
DSLRX08	.002	$	Oil changes

PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED [Required Products]

A24 [Product Reference]	A28 [Yield]* (%)	A26 [Ideal Ratio]** Of Units Out/Units In	A27 Units Of A26***	A25 Product Name
PlateW	.995	1	wafer / wafer	Ni plated cells
			/	
			/	

Prepared by John Wohlgemuth Date 8/81

* 100% minus percentage of required product lost.
** Assume 100% yield here.
*** Examples: Modules/Cell or Cells/Wafer.

operation. The equipment costs and material and utility useage estimates were all obtained from J. Weinberg of Technics.

Using the data on this Format A, we had calculated the cost per watt using the IPEG approximation. This analysis is based upon the following assumptions.

50 MW per year factory

15% eff. 10 cm x 10 cm cells = 1.5 watts each

Process yield (from wafer to module) = 93%

Summary of Ion Milling Cost:

Equipment =	$0.0054 per watt
Floor space =	$0.00096 per watt
Direct labor =	$0.0031 per watt
Materials =	$0.0012 per watt
Utilities =	$0.00027 per watt
Total =	$0.0109 per watt

This compares favorably with the estimate from the First Quarterly Report for laser scribing of $0.0139 per watt. Ion milling is not only cost competitive with laser scribing, but actually may lead to a cost reduction.

3.6 Tabbing and Stringing Machine

Tabbing and stringing machine proposals were receieved from Kulicke and Soffa, MB Associates, Spire/Kinematics and PROA/MRL. MB Associates was selected for negotiations and a contract was signed July 20th. The initial efforts included establishing a program work breakdown structure and schedule, preparing a program plan, and developing a test plan for the pulsed solder technique.

3.7 Encapsulation Experiments

The encapsulation efforts included work in the following areas:

- Insulation Tapes,
- Tape Applicators,
- Characterization of embossed EVA,
- Adhesive bonding of AMP connector to black polyethylene,
- Stability of MEPSDU cells under lamination conditions, and
- Thermal and optical properties of black polyethylene.

3.7.1 Insulation Tapes:

Wraparound interconnects require insulation between the wrapped around tabs and the back of the cells. Such insulation can be accomplished by placing a ½ inch wide tape along two edges of the cell before wrapping the contacts around the edge.

Exploratory experiments have provided specifications and desirable properties of such a tape in terms of ease of processing and the properites required. The dielectric needs to withstand the lamination process as well as the environmental tests. Environmental testing includes thermal cycling, -40°C to +90° and 95 percent humidity at 70°C. The lamination process can include pressures up to 15 psi at 150°C. The tapes must maintain electrical isolation across one cell or approximately 0.5 volts.

Pressure sensitive tapes consist of a polymeric film carrier and pressure sensitive adhesive. Due to the potential for bleeding of an adhesive compound into the EVA matrix and its subsequent UV or other environmental degradation, an acrylic adhesive was chosen as most desirable. A silicon adhesive (for example, the Kapton tape or Polken 721) is also known to be satisfactory for this use but they are expensive.

Originally we selected polyester, polyethylene and polypropylenes as possible candidates. Tedlar and other flurocarbons are not good candidates due to their high cost. Still other candidates like Teflon and Kapton are even more expensive. Reinforced materials have also been avoided because they provide a moisture path and lead to current leakage under humdid conditions.

It is also desirable for the pressure sensitive adhesive to stick both to the back of the cell and to the EVA matrix. Many pressure sensitive tapes have a release layer on the back of the carrier so that a tape roll can be unwound easily. This release backing will, of course, reduce the bondability of the adhesive carrier to the EVA matrix.

Thermal Cycling

The following tapes were subjected to thermal cycling for fifty or more cycles.

1. Polyken 832 polyethylene,
2. 3M 480 polyethylene,
3. Adhesive Research 55913 double face polyester,
4. Permacel P280 polyester,
5. 3M Y9769 double face polyester,
6. Permacel J-Lar III polypropylene,
7. Shuford PS748 polypropylene,
8. Permacel P234 polypropylene.

All of these tapes withstood the 50 cycles with no increase in leakage current.

Humidity Testing

The samples were subjected to humidity testing at 70°C 95 percent RH. Application of 1000V caused all of the acrylic tape samples to fail after a short exposure at this humidity. These also failed at 100V. Typical results are given in Table 6.

	Leakage at 1000 Volts (mA)
Polyken 832 polyethylene	0.31, 6.3
3M 480 polyethylene	6.3
3M 8057 polyethylene	6, 0.6
Permacel P280 polyester	0.47
Adhesive Research S5913 polyester	0.75, 0.35
Shuford PS-748 polypropylene	0.43, 0.43

Table 6. Hi Pot Tests After Several Hours in Humidity Exposure

While mA readings are failures, all the very high leakage readings for the polyethylene tapes may be explained as due to cutting into the polyethylene tape by the tab material during lamination which did not occur with the prestretched, orientated polyester or polypropylenes.

Since the maximum operating voltage the tape is expected to see is 0.5 volt subsequent experiments were conducted with a much lower voltage (10-25 volts). The results for 5 different tapes are shown in Table 7. Each of these candidates exhibit no leakage before or after thermal cycling. All five films exhibited acceptable leakage levels during the humidity tests.

Processing Stress Requirements

During lamination, the module and the tape are subjected to pressure and temperature stresses. In particular, the tab material may cut through the tape, particularly if the tape is not thick enough and/or is softened by the heat. To assess the tape edge puncture resistance, a test was designed in which tab strips were placed on each side of a piece of tape. The sandwich was laminated with EVA according to standard lamination practice, but applying a pressure of 15 psi.

The configuration of the edges of the interconnects were set to function as a possible worst example for cutting through the tape leaving no electrical isolation. The results are given in Table 8. It can be seen that the unoriented films, such as polyethylene and the thinner films, such as polypropylene P-23

Tape	Film Carrier	Adhesive	Thermal Cycling						Humidity							
			10			25			10				25			
Voltage DC																
Days			0	8	40	0	8	40	0	1	7	12	0	1	7	12
Keene HS2400	Polyester	Polyester Thermoplastic	0	0		0	0		0	.02 .02	.08 .44	.06 .07	0	.04 .04	.24 .28	.18 .14
P-234	Polypropylene	Acrylic	0	0		0	0		0	.09 .09	.07 .14	.09 .15	0	.08 .08	.25 .36	.14 .34
J-LAR 11	Polypropylene	Acrylic	0	0		0	0		0	.07 .07	.12 .11	.09 .09	0	.1 .1	.45 .30	.15 .24
781	Polyester	Silicone	0	0		0	0		0	.07 .07	.12 .11	.09 .09	0	.1 .1	.45 .30	.15 .24
832	Polyethylene	Acrylic	0	0		0	0		0	.05 .05	.09 .07	.11 .06	0	.06 .06	.32 .12	.17 .13

Table 7. Summary of Environmental Tests

Tape	Film Carrier	Adhesive	Maintenance of Electrical Isolation After Full Pressure Lamination
Polyken 832	Polyethylene	Acrylic	Fail
Polyken 832	Polyethylene	Acrylic	Fail
Polyken 832	Polyethylene, double layer	Acrylic	Fail
3M 8057	Polyethylene	Acrylic	Fail
3M 8057	Polyethylene, double layer	Acrylic	Fail
Permacel P234	Polypropylene (thin gauge 1)	Acrylic	Fail
Permacel JLAR11	Polypropylene (thicker gauge)	Acrylic	Pass
CHR M-50	Polyester (1 mil)	Acrylic	Fail
CHR M-57	Polyester (2 mil)	Thermoset	Pass
Permacel P255	Polyester (2 mil)	Rubber	Pass
Permacel P280	Polyester (1 mil)	Acrylic	Pass
Polyken 781	Polyester (1 mil)	Silicone	Pass
Polyken 781	Polyester, double layer	Silicone	Pass
Keene HS2400	Polyester (2 mil)	Polyester thermoplastic	Pass
Polyken 293	Glass cloth	Thermoset	Pass

Table 8. Lamination Pressure Test

and the 1 mil polyester M50 all fail. All the other tapes pass. Double taping with thinner tapes does not particularly help.

The following tapes have passed our environmental tests and are candidates for use.

- Lamart Corporation - 101-L, a 2 mil polyester tape with acrylic adhesive and a liner.
- Lamart Corporation - 107-L, a 2 mil white polyester tape with acrylic adhesive and a liner.
- Adhesive Research - S-5919, a 1.5 mil polyester tape with a 1.5 mil acrylic adhesive layer.
- Permacel - P-280, a 1 mil polyester tape with a 1.3 mil acrylic adhesive that must be wiped with a solvent to remove the release layer.
- CHR - M99, a 2 mil polyester tape with a 1.5 mil acrylic adhesive that must be wiped with a solvent to remove the release layer.
- 3M - 850, a 1 mil polyester tape with a 1.5 mil acrylic adhesive that must be wiped with a solvent to remove the release layer.
- Adhesive Research - S-5913, a 1 mil polyester tape with 1.5 mil acrylic adhesive on both sides and a liner.

- Keene - HS2400, a polyester film with a heat sealable polyester adhesive on one side and an acrylic transfer adhesive on the other.

Typical costs for these films are 2 to 4 dollars per 72 yard roll in small quantities (several cases).

3.7.2 Tape Applicators

Several tape applicator manufacturers have been contacted. They include two who manufacture standard taping equipment used in the printed circuit board industry. They are:

Western Magnum
Hermosa Beach, CA

and

Precision Industries
Cleveland, OH

These machines, with micrometer controls can apply a tape with a 5 mil projected tolerance. It is an accuracy barely within the scope of our requirements. We would like a 2-3 mil accuracy to ensure isolation at the wrap around edge.

In a normal operation, in taping a PC board two faces, top and bottom, are taped simultaneously from two rolls of tape. In our application, the second roll of tape would be replaced by a renewable paper roll.

We visited Western Electric, Richmond, Virginia, and observed their Precision Industries tape applicator. It was obvious that the nip rolls would crack the cells. The nip rolls are made of black rubber. This equipment has been made with silicone rubber rollers that can handle fragile material.

F. W. Winne & Company suggested the use of a die cut in which the machine would punch out the required piece and accurately place it. This operation may be applied to a configuration where the cell edge tape is back face up. The tolerance of such a die and its feasibility needs to be determined.

Spartanics, Ltd., Rolling Meadows, Illinois, offers an optional sensor which will allow die cuts of $\pm$ 1.5 mil tolerance, which is in our accuracy requirement. They claim semi-automation with some 1,000 parts/hour.

We have also contacted two custom manufacturers of taping machines: 3M, Minneapolis, Minnesota, and Tapelas, Farmingham, Massachussetts. We are awaiting their response.

3.7.3 Characterization of Embossed EVA

Solarex has received an experimental developmental run from Rowland Industries, Berlin, Connecticut, in which a nominal 1,000 lbs. of EVA 150 was compounded with Springborn's cure and stabilizer package, its A9918 formulation (Reference 3) as given below:

Elxax 150	100% weight percentage
Lupersoe 101	1.5
Tinurin 770	0.1
Nauguard P	0.2
UV-531	0.3

The EVA was extruded into an 18 mil embossed or matted sheet. The sheet is embossed to reduce the high blocking nature of non-embossed EVA as is available from Springborn. The embossed EVA substantially reduced the blocking and lay up blocking problems are avoided.

As part of our evaluation, sections of the film were submitted for Oscillating Disk Rheometery (ODR) evaluations according to ASTMD2084. For comparison, we have data on previously prepared embossed EVA as obtained from DuPont via Rowland. Comparative data are given in Table 9.

It had been reported that the original embossed EVA had parameters very close to the Springborn materials. The second batch of embossed EVA is much like the first except for the torque required when the film test sample is at full cure. The second batch is in the range of 20-30% higher. While the difference is acceptable, the higher torque value may be associated with an increase in cross link density due to a better dispersion of the additives. Additional tests are underway including a repeat ODR analysis using a second source and covering all four temperatures, 202^{o}C, 180^{o}C, 150^{o}C, 140^{o}C, of our previous data.

Table 9. ODR Data on Two Batches of Embossed EVA

	#1 Maximum Torque lb/in		#2 Cure Time Time to 90%		#3 Scorch Time (Minutes)	
Temperature	202°C	185°C	202°C	185°C	202°C	185°C
Embossed EVA (DuPont batch)	29.7	24.4	3.3	7.3	.85	1.3
Embossed EVA (Rowland's recent batch)	33.0	36.7	3.1	7.0	.77	1.15

#1 A measure of the tensile modulus of the compound.

#2 Time required to reach 90% of full torque value.

#3 Time when the coupling reaction starts to crosslink.

3.7.4 Adhesive Bonding of AMP Connector Box to Black Polyethylene

Because polyethylene has a low surface energy, it is difficult to adhere the AMP connectors to the back of the module. The connector itself is made of weatherable grade black nylon. The surface which is bonded to nylon is an embossed surface to increase total surface area and mechanical bonding.

A number of adhesives between the amp connector and the polyethylene have failed the environmental tests of 70°C-95 percent relative humidity and thermal cycling -40°C to +90°C. These include silicones, GE's RTV 108, and epoxies, urethane modified epoxy, Cyanamids Cybond 1110, and Hughson's Versilok 506 and 3M's 3501. Corona discharge treatment of the polyethylene surface has substantially increased the ability of the adhesives to stick to this polyethylene. The failure that did occur following the corona treatment was only after several days in the humidity chamber.

An alternative method to activate the polyethylene surface as an adherent surface was to place a small 2 x 2" square of EVA film external to the polyethylene at the spot at which the connector will be attached. The EVA was pressed into the polyethylene during lamination resulting in a good bond between EVA and the polyethylene surface. Adherence to the EVA surface was no better than to the black polyethylene surface, when using RTV 108 as the adhesive. Additional experiments are planned using the EVA patch.

Additional experiments are also planned with urethane adhesives and with acrylic transfer adhesives. It should be noted that urethane will be accompanied by a cross linking reaction. That is the adhesive bond itself will become thermoset.

One adhesive which we have found effective is a hot melt (140°C) thermoplastic elastomeric adhesive based on Phillip's Solaprene as supplied by B. F. Goodrich PL804. After prolonged humidity tests this system could only be separated by application of significant prying force. The failures of other systems were immediate, requiring essentially no force.

The disadvantage with the thermoplastic elastomeric hot melt is the requirement of applying it in production. There are, of course, many commercial applications of hot melts and specialized applicators are available. At high production rates such an application is very feasible. Work is underway to: 1) identify a thermoplastic elastomeric which has a lower application temperature and performs as well, and 2) identify methods of application applicable to small runs.

3.7.5 Stability of MEPSDU Cells Under Lamination Conditions

The question has been raised as to whether the heat used during EVA encapsulation would make the cells less efficient. I-V curves were taken of three MEPSDU cells. The cells were the subject to 167°C for thirty-four (34) minutes, a temperature which exceeds lamination temperature and the approximate time of such a lamination. No change in IV curve was observed on repeat measurements of the three cells. Therefore it appears that lamination conditions do not effect cell performance.

3.7.6 Thermal and Optical Properties of Black Polyethylene

An experiment was performed to determine the cell temperature effect of a black polyethylene-backed vs. a white Tedlar-backed module. Two 2 ft. x 4 ft. practice modules were used which had reject cells arranged approximately in the same pattern they would be in a regular module. As a basis for setting up the data taking, we used the procedures specified in JPL documents for determining NOCT (Nominal Operating Cell Temperature). These modules were set up side by side about a foot apart.

The results of the data are plotted in Figure 3. The cell temperature was determined by averaging two readings from thermocouples attached to cells.

From these data we can make the following conclusions:

- The black-backed module had consistently higher temperature readings than the white-backed module.
- The NOCT based on this data is:
  White backed - 41.5°C
  Black backed - 43.2°C (Both at 80 mw/cm^2 illumination)

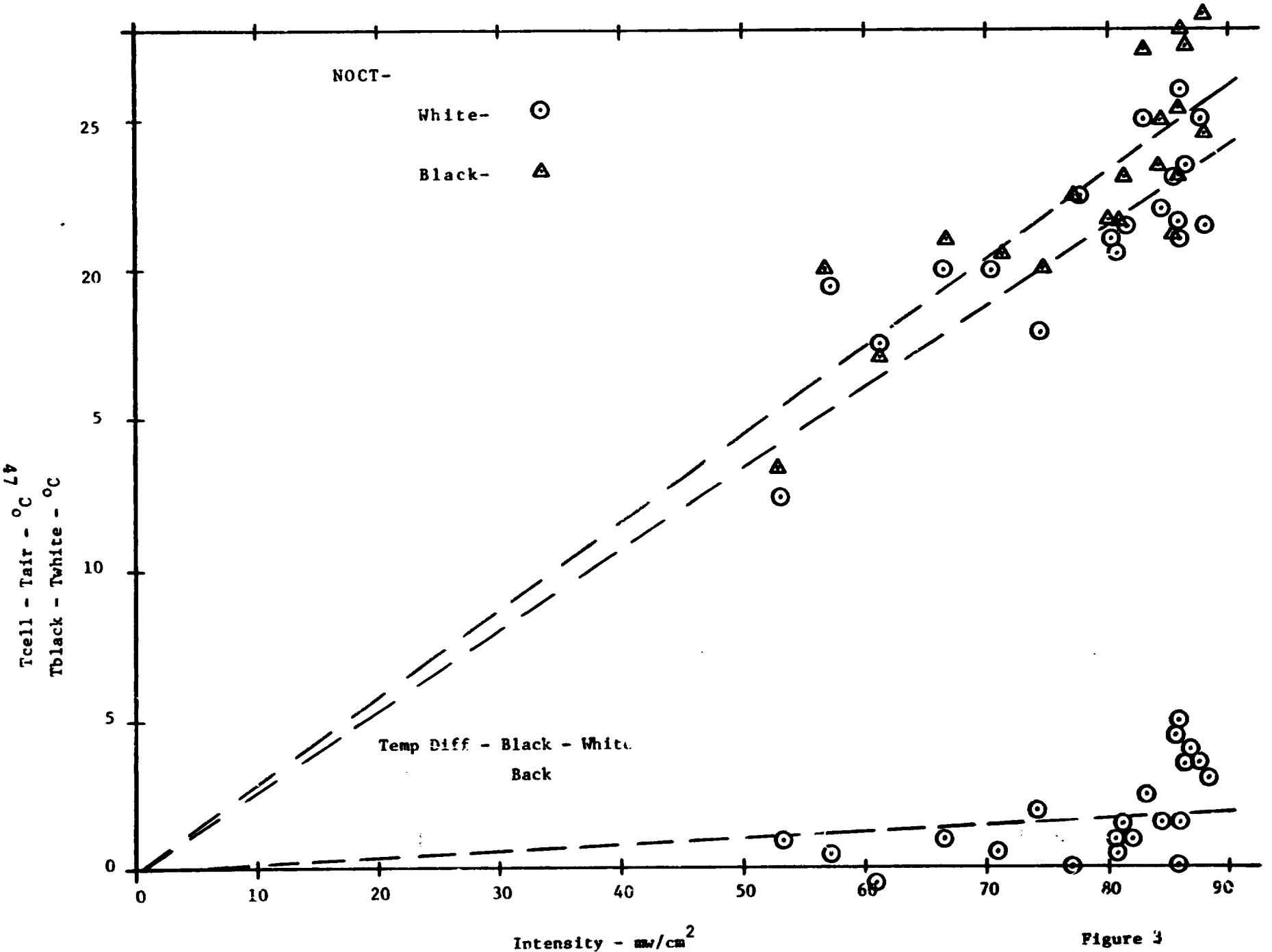

NOCT-
White-
Black-
25
20
5
10
5
0
Tcell - Tair - °C
Tblack - Twhite - °C
Temp Diff - Black - White
Back
0
10
20
30
40
50
60
70
80
90
Intensity - mw/cm²

Figure 3

- The temperature difference between the black and white is 1.7°C.

The actual value of NOCT is not particularly accurate, since there was no correction for wind velocity and because the modules were not mounted within an array. However, the temperature difference should be a fairly accurate indicator of the true difference of temperature between the two different modules.

Thermocouples were also mounted to the back of the module. The temperatures were consistently within 2°C (cooler) of the cell temperature on the module. This shows that we can get a good approximation of the cell temperature without cutting into the module.

To determine the cost effectiveness of using black polyethylene, we have calculated the power loss due to its use and compared this with the cost savings associated with its use. The results indicate that with a module cost of $2.70 or less there is a cost savings gained by using the black polyethylene.

We have also begun work to measure the difference in output of the same module as a function of the color of the backing material. Clear, white, blue and black are all being investigated. Outdoor measurements indicated there was only a marginal difference (less than 1%) between the highest (white) and the lowest (black) backing.

The experimental errors associated with the measurement are larger than the measured difference between the 2 backings. Based on these measurements, black polyethylene is a viable material for use as the backing material.

3.8 Equipment Vendors

A number of vendors have been contacted in regards to the equipment necessary to build the MEPSDU process line. A list of these vendors is given in Table 10. Quotations have been received from most of these vendors.

TABLE 10

Vendors Contacted

Etch System	Conveyor Engineering Frederick Manufacturing Western Technology Crest Ultrasonics
Spray Coaters (2):	ITI Advanced Concepts Corp.
Belt Furnaces (2):	BTU Engineering Thermco Infrared Furnace Systems
Screen Printers (2):	AMI DeHaart
Sand Blasting Equipment:	MTI Empire
Plating Transport System:	Conveyor Engineering Branson Corp. Crest Ultrasonics
Wave Solder Equipment	Electrovert Hollis
Wafer Handling:	Kinematics PROA DeHaart AMI
Laser Scriber	Quantrad
Plasma Etch:	Technics
Xenon Light Source:	Oriel Schoeffel Xenon Corp.
Laminator	Solarex Design Spire
Module Lay-up System	Solarex Design MBAssociates

4.0 Recommendations and Schedule

The following technical questions must still be answered:

- To develop a method to assure that the wraparound contacts do not short on top edge of cell,
- To get our wave solder machine operational and to make cells using the sand blast-wave solder technique,
- To optimize all the processes, especially the solder thickness control for maximum cell performance,
- To develop a satisfactory technique for adhering the amp connector to the black polyethylene backing.

The following efforts will be undertaken during the next program period:

- Rescheduling of the program to accomodate the reduced spending rate and charge in scope of work,
- Completion of the pilot run 4, and,
- Collection of data for preliminary Samics analysis.

REFERENCES

1. Solarex Corporation, A Module Experimental Process System Developmental Unit (MEPSDU), First Quarterly Report, February 1981, JPL Contract No. 955902.

2. Solarex Corporation, A Module Experimental Process System Developmental Unit (MEPSDU), Second Quarterly Report, May, 1981, JPL Contract No. 955902.

3. Springborn Corporation, "Investigation of Test Methods, Material Properties and Processes for Solar Cell Encapsulants", Annual Report, June, 1979, JPL Contract No. 954527.